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AUTHOR	Klahr, David
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INSTITUTION	Carnegie-Mellon Univ., Pittsburgh, Pa. Dept. of Psychology.
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ABSTRACT

This paper presents a theory of human information processing. Information processing refers to the perception, encoding, recoding, storage, retrieval and manipulation of information by the brain. This theoretical model takes a developmental perspective in explaining human performance on tasks that require thinking, reasoning and remembering. Answered is the question of how information is processed by adults and by children of different ages. The main focus of this paper is upon those features of the theory which attempt to answer the questions of how and why do the differences between children and adults disappear with development. (SJL)

DEPARTMENT

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Notes on
A Theory of the
Development of the Human
Information Processing System

by

David Klahr
Carnegie-Mellon University

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This paper is a very slightly edited version of a talk presented at the 1975 meetings of the American Psychological Association, Sept., 1975, Chicago, Illinois. The research described here has been supported in part by the Spencer Foundation.

Over the past 5 or 6 years Iain Wallace and I have formulated a theory of the development of the information processing system. It is a particular way of looking at cognitive development that attempts to apply and extend the conceptual and methodological approach of the information processing work pioneered by Newell and Simon to the set of problems most eloquently stated by Piaget. Although bits and pieces of our theory have appeared in various places (Klahr, 1973a, b,c, 1976; Klahr & Wallace, 1970a,b, 1972, 1973), we have finally brought it all together in a book that will appear early next year (Klahr & Wallace, 1976).

I now have 20 minutes to summarize over 100 thousand words. All I will attempt to do here is tell you a little bit about the nature and scope of the theory, and some of its central features.

First, what do we mean by an information processing theory? In our context, information processing refers to the perception, encoding, recoding, storage, retrieval and manipulation of information by the brain. The emphasis in our theory is on the symbolic and logical form of such operations, and not on the underlying physiological substrata.

Information processing theories are derived from human performance on tasks that require thinking, reasoning, and remembering. These are typically complex tasks such as concept formation, sequential pattern induction, game playing, numerical and logical puzzles, and reasoning tasks. Of course, in the Genevan tradition, this includes tasks such as seriation, conservation, and so on. It is, in our view, virtually impossible to explain performance on such tasks without postulating some sort of human information processing system.

We can characterize scientific inquiry into children's information processing abilities as a search for the answer to three related questions.

1. How is this task done by adults?

   (Or by children of different ages? This is the so-called "stage" question.)

2. Are there differences between children and adults?

   (This is the other part of the stage question)

3. How and why do the differences disappear with development?

   (This is a way of stating the "transition" question.)

In this brief discussion of our theory, I will summarize the answer to question 1; I will assume that you are familiar with the vast empirical literature on question 2; and I will focus mainly upon the features of our theory which attempt to provide some answers to question 3.

It is worth noting that our goal of producing an answer to the transition question constrains the kind of answer we can produce to the question about the form of the adult system. That is, it is entirely unsatisfactory to create a theory of the mature information processing system for which there appears to be no plausible developmental mechanism. I will return to this point several times in my subsequent comments.

What does the adult information processing system look like?

Although there are still many points of disagreement among researchers in the field, in the past 20 years there has emerged a consensus about the general structure of the human information processing

system. Figure 1 shows one representation of the system, adapted from Newell and Simon (1972), and Hunt ( ).

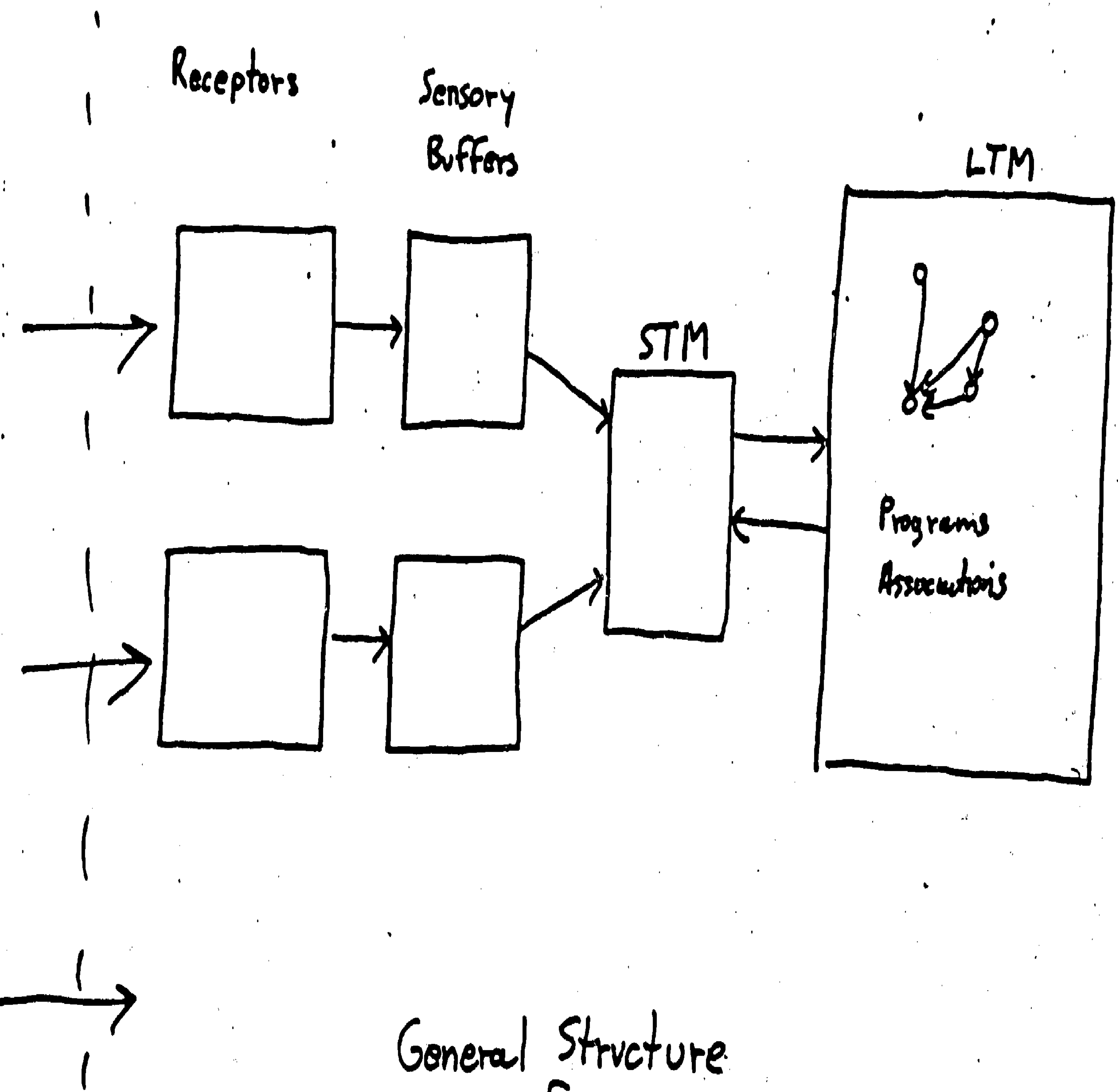
Processing is postulated to occur in a sequence of layers, starting with environmental stimuli impinging on the senses, and continuing on to the "deeper" or "central" processes. Associated with each layer is some storage capacity (a buffer) which holds information while it is further processed by subsequent stages. At the outer layer, are the sensory processes, which receive and briefly store, for fractions of a second, all sensory information. Up to this point the system appears to operate in parallel and unselectively. At the next level, selected and partially encoded information is retained for further processing by modality specific (e. g. visual or auditory) buffers, for somewhat longer periods of about one second duration.

Next, information is passed through a limited capacity buffer, usually identified as short term memory (STM). Information in STM must be attended to and retained for some period, from 5 to 10 seconds, before it can be transferred to long term memory (LTM).

LTM appears to be of essentially unlimited capacity. It is organized as a network of associated concepts and propositions, and a collection of strategies and procedures. The routines in LTM control information transfer among the layers of processing, the searching of the conceptual and propositional network and programs for the modification of LTM.

The young information processing system

So much for the adult information processing system. How shall we characterize the child? We face one overwhelming fact: On almost



General Structure of Human IPS

Figure 1

any task presented to them, children's performance is poorer than adult's: they are slower, they make more errors, they don't attend or remember as well. However, for children beyond the age of five, there is no reason to believe that the system architecture just outlined -- parallel sensory buffers, limited STM, and unlimited associative LTM -- changes with age. An even stronger view, which we endorse, is that there is no substantial change in the parameters, e. g. the capacities and rates, of the components of this system architecture.

The major difference between children and adults is that children appear to be deficient in prior knowledge of facts, procedures, strategies, in control of attention, and in utilization of memorial processes. These operations all derive from programs in long term memory. Thus, the central focus of our theory is a representation of the knowledge in LTM, and a theory of how that representation is changed to permit increasingly powerful performance within a relatively unchanging system architecture.

Representation of knowledge

Our representation for knowledge in LTM takes the form of a production system. A production system is a formalism for expressing how an information processing system might respond to the momentary state of knowledge in which it finds itself: that is, how it might determine what to do next, given what it now knows. The basic unit is a production. A production is a rule that consists of a condition and an associated action. The condition tests the instantaneous knowledge-state of the system: i. e. the current contents of its buffers,

If a condition is satisfied, then its actions are executed, changing the state of knowledge. A collection of productions that serve some specific function is called a production system. There are several ways the set of productions can be organized and coordinated to produce some purposeful piece of information processing. The level of detail, and hence the grain of the time- ce accounted for by productions, varies from 30 to a few hundred milisecs in the models that have been proposed. (For an introduction to production systems see Newell, 1973 or Klahr, 1976).

In our model (see Fig. 2), the condition sides of productions can test various combinations of buffers at deeper and deeper layers along a single modality, or they can contain cross modal referents. Ultimately, these encoding productions place symbols in what we call semantic short term memory. Although it is too complex to go into here, it is this kind of representation that has finally enabled us to account for the difference in the rate of so called immediate apprehension or "subitizing" (40 ms per operation) and the rate of what we typically call counting (300 ms)(Chi & Klahr, 1975). Subitizing takes place via productions that operate upon visual STM in a template-matching sort of fashion, and counting takes place via the sequential recognition of items in semantic STM (Chap. 3 of Klahr & Wallace, 1976a). Similarly, the establishment of a target item in something like a class inclusion task can be accounted for by a mixture of productions operating on both the auditory and the visual buffers to produce a representation of the task in semantic STM.

All knowledge in our system is represented by productions and

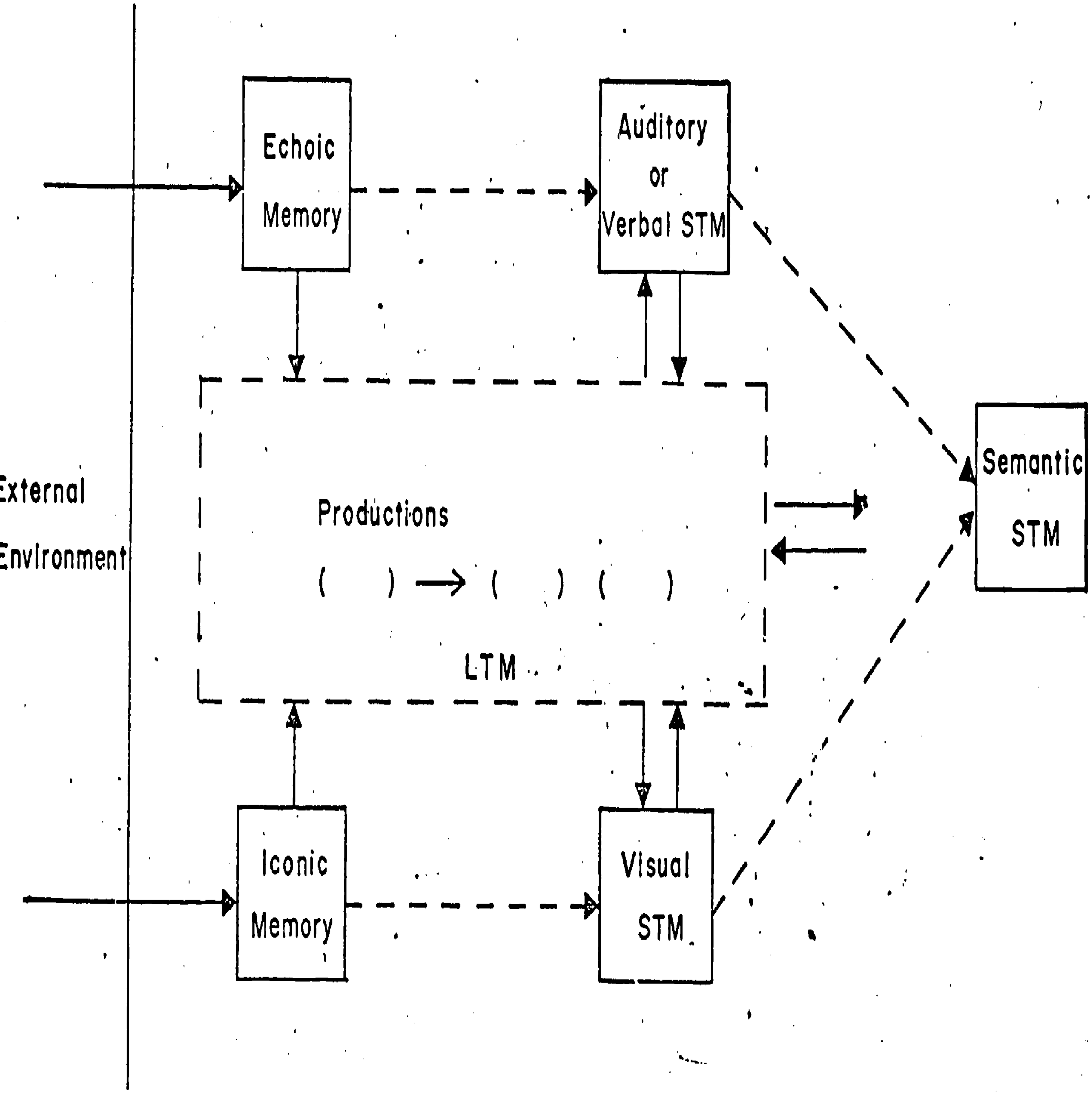

Echoic Memory
Auditory or Verbal STM
External Environment
Productions
( ) → ( ) ( )
LTM
Semantic STM
Iconic Memory
Visual STM

Figure 2

production systems. Objects are represented by the tokens corresponding to the productions that are consistantly evoked when the objects are presented to the system. In addition they have some descriptive symbols attached to them, corresponding to information about their properties such as color or size. These values are in turn represented by the same kind of production system structure, and so it goes up through high level generalizations such as attribute names like shape (see Fig. 3). The details of this representation are not important here: suffice it to say that they are functionally similar to many current representations for associative memories, such as models of semantic memory, and in addition, they are represented in terms of productions.

The sheer magnitude of the proposed collection of productions requires that we place a plausible structure on LTM. The structure we propose has implications for the temporal sequence in which productions are tested to see if they can fire. LTM is divided into three tiers, and within each tier there are multiple levels (see Fig. 4). The tiers are searched in sequence, starting with Tier 1. Within each tier, each level is also tested sequentially. However, in a given level, the search for true productions takes place in parallel. Finally, once a production system is activated, search is again sequential.

Each tier contains systems that serve different functions and arise from different aspects of development. Tier 1 contains the results of specific experience encountered by the system. Fig. 3 shows the kinds of things that could be in the various layers of the first tier. Tier 2 contains a repertoire of general problem solving strategies and procedures, such as means-ends analysis, factorization,

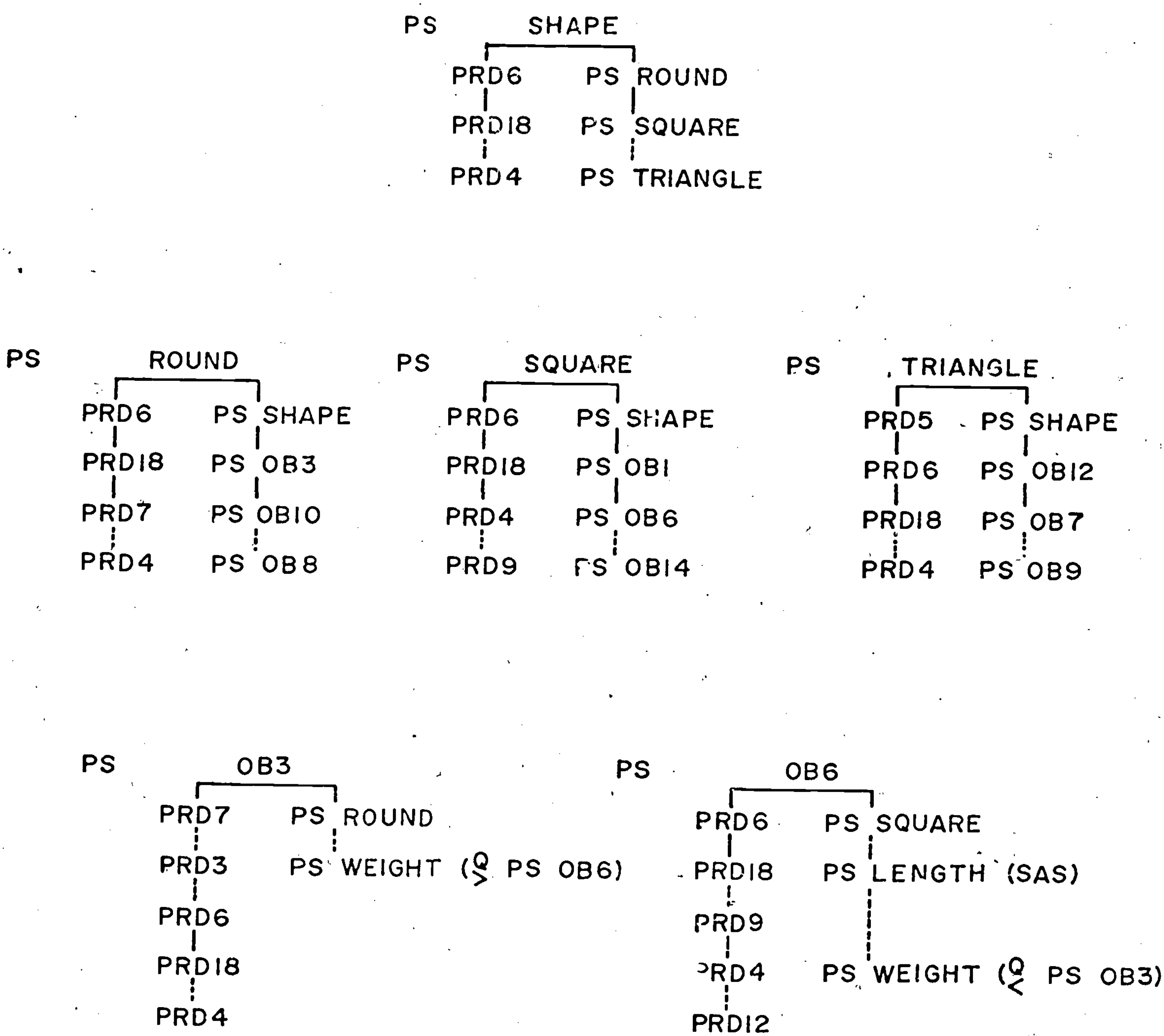

PS SHAPE
PRD6 PS ROUND
PRD18 PS SQUARE
PRD4 PS TRIANGLE
PS ROUND
PRD6 PS SHAPE
PRD18 PS OB3
PRD7 PS OB10
PRD4 PS OB8
PS SQUARE
PRD6 PS SHAPE
PRD18 PS OB1
PRD4 PS OB6
PRD9 PS OB14
PS TRIANGLE
PRD5 PS SHAPE
PRD6 PS OB12
PRD18 PS OB7
PRD4 PS OB9
PS OB3
PRD7 PS ROUND
PRD3 PS WEIGHT (Q > PS OB6)
PRD6
PRD18
PRD4
PS OB6
PRD6 PS SQUARE
PRD18 PS LENGTH (SAS)
PRD9
PRD4 PS WEIGHT (Q < PS OB3)
PRD12

Figure 3

Structure of LTM

		Content
TIER 1	LEVEL 1 ↓ LEVEL 2 ↓ LEVEL 3	Productions and production systems derived as result of specific experience of individual IPS.
TIER 2	LEVEL 1 ↓ LEVEL 2 ↓ LEVEL 3	Repertoire of problem solving strategies available to IPS.
TIER 3	LEVEL 1 ↓ LEVEL 2 ↓ LEVEL 3	Productions and production systems underlying self-modification capability of IPS.

Figure 4

and so on. Finally Tier 3 contains the systems that underlie the self-modification capacity: i. e. they contain the productions that allow cognitive development to take place.

So much for the statics of LTM, now for the dynamics. (Note the ambiguity fo such a distinction in a developing information processing system.) We need one additional feature for our system to have a capacity to develop. In just a moment I will describe several mechanisms that account for self-modification. They will all be directed toward the creation and addition of new productions to various parts of LTM, and the central question will be the information source that tells the system when to add these new productions. The system must have some means of monitoring its own activity in order to answer this question. The mechanism we propose uses something we call the "time line".

The time line contains a sequential,symbolic, record of the system's activity. At the conclusion of each processing episode, information about the initial and final states of the buffers involved with that episode are placed in the time line.

The time line thus provides an encoded representation of the sequential states of the information processing system. If any regularities exist in the interaction of the system with the environment, they will be represented in the time line. Self modification takes place through the detection of this regularity and the subsequent addition to the system of productions that will capitalize upon it.

Acquisition of knowledge

Now we can talk about development. Let's start at the beginning. What's innate? We postulate a kernal of innate productions in each

of the three tiers, but I will only have time to discuss some of the features of one such set, the tier 3, or self modification productions. One general principle governs the operation of the self-modification productions. The principle is a least effort or "processing economy" principle. The system has such a limited capacity workspace, and such a huge LTM, and such a complex environment, that it endeavors at all times to make the symbols with which it is dealing as information laden as possible. Similarly, it attempts to construct programs that will minimize the amount of processing necessary to do a given task. There are three major ways that the system achieves this goal of efficient processing:

Consistency detection

Redundancy elimination

Global orientation

By consistency detection, we mean the discovery by the systemic productions that a set of specific sequences can be accounted for by some higher order rule.

By redundancy elimination we have in mind the kind of efficiency described in Baylor's work (Baylor & Gascon, 1974) on seriation or by the discovery of short cuts by children who face the same set of steps in a task repeatedly.

By global orientation, we mean the tendency for children to process objects as integrated wholes unless they keep failing. Only then do they resort to a dimensional treatment of the stimulus materials.

In the very brief time remaining let me try to give you a feeling

for the nature of the mechanism that implements these general principles. Consider some of the current models for sequential pattern induction. The general approach is to view such an induction process as one in which simple regularities are sought in the pattern. Once partial regularities are detected, the system attempts to work on the fine structure of the relationship among elements in the pattern. The simplest case consists of a single dimension, and no external system of orderings: e. g. color sequences R Y Y R Y ___. Additional complexity in patterns (and in the induction rules) comes from either multi-dimensional objects (e. g. color and orientation: RU YD YU RU YD___) or external alphabets (e. g. the English alphabet), or number systems that have sets of rules for complex relations associated with them. Even more complexity comes from a relaxation of the requirements for identity, so that systems can now find "sames" that are really equivalence classes (e. g. letter series in slightly different type-faces) or partial matches.

Now view the symbols in the time-line as a sequence in which our system is attempting to detect some consistencies. In general, all of the complications just mentioned will occur, as well as a conflict between the frequency of near matches and the degree of fit, e. g. many poor fits vs. few good ones. In a system that is attempting to form a new production that says, in effect, "when you know X do Y," the abstraction of what constitutes an appropriate X or Y depends upon a precise model of how this complex sequence detection process works. In our theory we attempt to spell out some of the properties of this model of abstraction: it is one of the central mechanisms in our theory of the development of the information processing system.

Elaborate examples of this consistency detection procedure are presented in chapters 5 and 6 of our book (Klahr & Wallace, 1976a), and

a preliminary account of some of the mechanisms can be found in Klahr & Wallace, 1973.

How concrete are the current formulations of the general theory just described? What do we have in the way of running programs in our theory? Although we have scarcely mentioned them, our theory has been built upon and modified by, running models, written as production systems of performance on the classic Genevan tasks: class inclusion, conservation, transitivity, as well as detailed models of elementary quantification tasks. So there are pieces of performance models for different levels of performance on different tasks. We have no running program for our model of self-modification (although some very simple ones, written as self modifying production systems have been created by my colleague Don Waterman, 1974). Thus our general theory is stated at a metaphorical level. However, the performance systems that we do have are consistent with the developmental theory. This gives us reason to believe that we will soon be able to implement the developmental part, and see it generate, as it experiences its environment the various stage models which we now have in running form.

Postscript

This paper was originally intended only for the verbal presentation at APA. The severe time constraints made it impossible to give more than a hint of what our theory really looks like. If you have found this "free sample" interesting, then I recommend either the "large economy size" presented in the book (Klahr & Wallace, 1976a) to appear early next year or the "regular size" which will appear as a chapter in a book (Klahr & Wallace, 1976b) late in 1976.

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